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LEAN LIMIT PHENOMENA

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Extensive theoretical and experimental research have been accomplished on the various aspects of the structure and extinction of premixed flames. The presentation will focus on only one specific topic of the lean/rich limit phenomena, namely the concept of flammability limits in the presence of flame interaction, and the existence of negative flame speeds. Attention is called to other topics reported in the publications listed; contributions from them are no less significant but will not be presented due to the lack of time.

To appreciate the importance of flame interaction, we first note that although predictions of complex flame phenomena are frequently based on understanding of isolated flames, it is clear that in most situations the combustion flow field is composed of an ensemble of flamelets, of different intensity and extent, which continuously interact with each other and thereby can cause significant modifications of the bulk combustion behavior.

In the present investigation downstream interaction between two counterflow premixed flames of different stoichiometries are experimentally studied. Various flame configurations are observed and quantified; these include the binary system of two lean or rich flames, the triplet system of a lean and a rich flame separated by a diffusion flame, and single diffusion flames with some degree of premixedness. Extinction limits are determined for methane/air and butane/air mixtures over the entire range of mixture concentrations.

The results show that the extent of flame interaction depends on the separation distance between the flames which are functions of the mixtures' concentrations, the stretch rate, and the effective Lewis numbers ( $Le$ ). In particular, in a positively-stretched flow field  $Le < 1$  ( $> 1$ ) mixtures tend to interact strongly (weakly), while the converse holds for flames in a negatively-stretched flow.

An important consequence of flame interaction is the modification of the flammability limits of a mixture when it is stratified. If the mixture is only weakly stratified, then the conventional flammability limits for uniform mixtures may still apply. However, with more extensive stratification the stronger portion of the mixture may burn independent of the weaker portion, while the weaker portion can also burn by receiving support from the stronger flame. The mixture is made more flammable as a whole.

Our study has also established the existence of negative flames whose propagation velocity is in the same general direction as that of the bulk convective flow, being supported by diffusion alone. Their existence demonstrates the tendency of flames to resist extinction, and further emphasizes the possibility of very lean or rich mixtures to undergo combustion.

Flame interaction is also of relevance to the modeling of turbulent flames. Within a turbulent flow field stratifications in temperature and reactant concentrations invariably exist, caused by mixing inhomogeneities or, more subtly, through the coupling between stretch and preferential diffusion even for an initially homogeneous mixture. Thus a flame kernel initiated within a turbulent eddy will manifest effects of downstream interaction between flames of different intensities.

#### Publications

1. "Effects of Heat Loss, Preferential Diffusion, and Flame Stretch on Flame-Front Instability and Extinction of Propane/Air Mixtures," by S. Ishizuka, K. Miyasaka, and C. K. Law, Combustion and Flame, Vol. 45, pp. 293-308, (1982).
2. "On the Opening of Premixed Bunsen Flame Tips," by C. K. Law, S. Ishizuka, and P. Cho, Combustion Science and Technology, Vol. 28, pp. 89-96, (1982).
3. "On Stability of Premixed Flames in Stagnation-Point Flow," by G. I. Sivashinsky, C. K. Law, and G. Joulin, Combustion Science and Technology, Vol. 28, pp. 155-159, (1982).
4. "An Experimental Study of Extinction and Stability of Stretched Premixed Flames," by S. Ishizuka and C. K. Law, Nineteenth Symposium on Combustion, the Combustion Institute, Pittsburgh, Pa., pp. 327-335, (1983).
5. "Heat and Mass Transfer in Combustion: Fundamental Concepts and Analytical Techniques," Proc. of ASME-JSME Joint Thermal Engineering Conference, (Y. Mori and W. J. Yang, Ed.), Vol. 2. pp. 535-559, (1983). \*\* Plenary Paper\*\*
6. "An Invariant Derivation of Flame Stretch," by S. H. Chung and C. K. Law, Combustion and flame, Vol. 55, pp. 123-125 (1984).
7. "Extinction of Premixed Flames by Stretch and Radiative Loss," by S. H. Sohrab and C. K. Law, to appear in International Journal of Heat and Mass Transfer.
8. "On the Determination of Laminar Flame Speeds from Stretched Flames," by C. K. Wu and C. K. Law, submitted.
9. "An Experimental Investigation on Flame Interaction and the Existence of Negative Flame Speeds," by S. H. Sohrab, Z. Y. Ye, and C. K. Law, submitted.
10. "Effects of Preferential Diffusion on the Burning Intensity of Curved Flames," by M. Mizomoto, Y. Asaka, S. Ikai, and C. K. Law, submitted.

OVERALL OBJECTIVES

1

- o TO UNDERSTAND THE FUNDAMENTAL MECHANISMS GOVERNING EXTINCTION OF PREMIXED FLAMES.
- o TO QUANTIFY FLAMMABILITY LIMITS OF MIXTURES AND IDENTIFY DOMINANT MECHANISMS IN OPERATION AT THESE LIMITS.
- o TO IDENTIFY POSSIBILITIES OF EXTENDING THESE EXTINCTION/FLAMMABILITY LIMITS.

POTENTIAL EXTINCTION MECHANISMS

2

- o HEAT LOSS.
- o KINETIC TERMINATION.
- o FLAME STRETCH:
  - FLOW NONUNIFORMITY
  - FLAME CURVATURE
  - FLAME ACCELERATION

PREVIOUS CONTRIBUTIONS

3

- o FLAME STRETCH, COUPLED WITH PREFERENTIAL DIFFUSION (NON-UNITY LEWIS NUMBER) EFFECTS, WAS IDENTIFIED TO BE THE DOMINANT MECHANISM IN OPERATION AT THE FLAMMABILITY LIMITS.
- o FLAMMABILITY LIMITS, DETERMINED BY USING THE COUNTERFLOW FLAME, AGREE WELL WITH EXISTING DATA.

PRESENT ACCOMPLISHMENTS

4

- o IDENTIFIED AND QUANTIFIED THE IMPORTANCE OF FLAME INTERACTION.
- o IDENTIFIED THE EXISTENCE OF LAMINAR FLAMES WITH NEGATIVE FLAME SPEEDS.
- o STUDIED EFFECTS OF FLAME CURVATURE ON BURNING INTENSITY.
- o CRITICALLY RE-EXAMINED EXISTING METHODS IN LAMINAR FLAME SPEED DETERMINATION; PROPOSED NEW METHODOLOGY.
- o THEORETICAL STUDIES ASSOCIATED WITH THE ABOVE TOPICS.

IMPORTANCE OF FLAME INTERACTION

5

- o PRACTICAL COMBUSTION FLOW FIELDS CONSIST OF ENSEMBLES OF FLAMELETS.
- o INDIVIDUAL FLAMELETS BURN WITH DIFFERENT INTENSITY AND EXTENT.
- o INTERACTION BETWEEN THEM CAN EITHER CONTRACT OR WIDEN THE EXTINCTION LIMIT.
- o ESPECIALLY RELEVANT TO TURBULENT FLAME MODELING AND FLAME PROPAGATION IN FLOWS WITH CONCENTRATION STRATIFICATION OR POOR MIXING CHARACTERISTICS.

## METHODOLOGY

- o ESTABLISH TWO PREMIXED FLAMES OF UNEQUAL STRENGTH BY THE COUNTERFLOW OF TWO STREAMS WITH DIFFERENT MIXTURE CONCENTRATIONS.
- o MAP THE FLAME CONFIGURATIONS AND EXTINCTION LIMITS AS FUNCTIONS OF STRETCH AND FUEL CONCENTRATIONS OF THE UPPER ( $\Omega_U$ ) AND LOWER ( $\Omega_L$ ) STREAMS.
- o MEASURE THE TEMPERATURE PROFILE FOR THE INTERACTING FLAMES.

## EXTINCTION LIMITS (METHANE-AIR MIXTURES)

- o FOR  $\Omega_L < 4\%$ ,  $\Omega_U \approx 6\%$  AND IS INSENSITIVE TO  $\Omega_L$ ; WEAK INTERACTION; STRONG FLAME BURNS INDEPENDENTLY, WEAK FLAME PARASITIC.
- o FOR  $4\% < (\Omega_L, \Omega_U) < 6\%$ ,  $(\Omega_L + \Omega_U)/2 \approx 5\%$ ; STRONG INTERACTION; SYMBIOTIC COMBUSTION.
- o INTERACTION IS STRONG (WEAK) FOR LEAN (RICH) MIXTURES.
- o THEORY SUBSTANTIATES THE ABOVE BEHAVIOR.

## PRACTICAL CONCLUSIONS

- o METHANE-AIR MIXTURES LEANER THAN 5% REMAINS NON-FLAMMABLE IF CONCENTRATION STRATIFICATION (OR MIXING INHOMOGENEITY) IS WITHIN 4-6%; A HIGHER STRATIFICATION WILL INDUCE BURNING.
- o MIXTURES ABOVE 6% WILL ALWAYS BURN, HENCE AUGMENTED FLAMMABILITY LIMIT.
- o INTERACTION IS STRONG (WEAK) FOR LEAN (RICH) MIXTURES.
- o FLAMMABILITY LIMITS LESS (MORE) SUSCEPTIBLE TO CONCENTRATION STRATIFICATION FOR LEAN (RICH) MIXTURES.
- o PROPANE-AIR AND BUTANE-AIR MIXTURES BEHAVE OPPOSITE TO METHANE-AIR MIXTURES.
- o MIXING INHOMOGENEITY PROMOTES BURNING.
- o EXISTENCE OF NEGATIVE FLAME SPEEDS DEMONSTRATES THE RESISTENCE OF FLAMES TO EXTINCTION.
- o FLAME STRETCH AND PREFERENTIAL DIFFUSION ARE CRITICAL FACTORS IN DETERMINING FLAME CHARACTERISTICS, ESPECIALLY EXTINCTION.
- o FRACTIONAL DEVIATION OF LEWIS NUMBER FROM UNITY CAN CAUSE SAME EXTENT OF DEVIATION OF FLAME TEMPERATURE.

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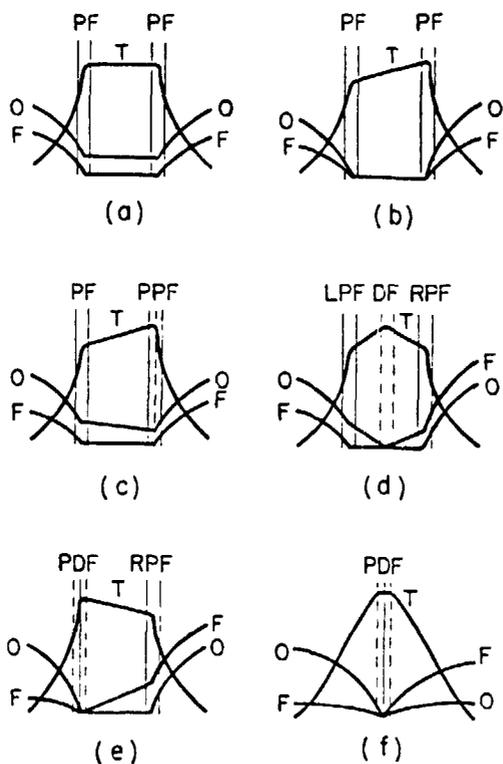


Figure 1. Possible modes of downstream interaction between two premixed flames. PF: Premixed Flame; DF: Diffusion Flame; LPF/RPF: Lean/Rich Premixed Flame; PPF: Partially Premixed Flame; PDF: Partial Diffusion Flame.

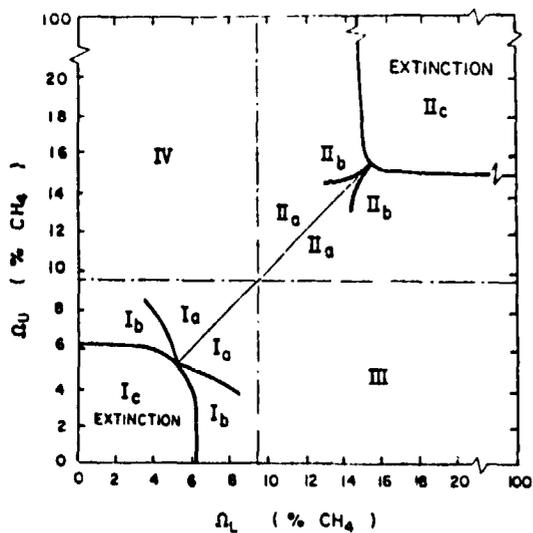


Figure 2. Mapping of the flame configurations and extinction boundaries for methane/air mixtures.

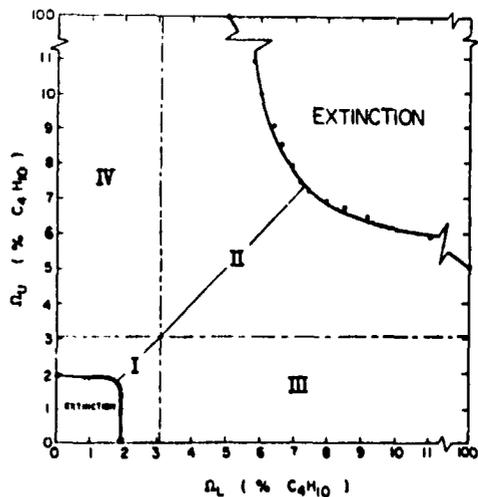


Figure 3. Mapping of the flame configurations and extinction boundaries for butane/air mixtures.

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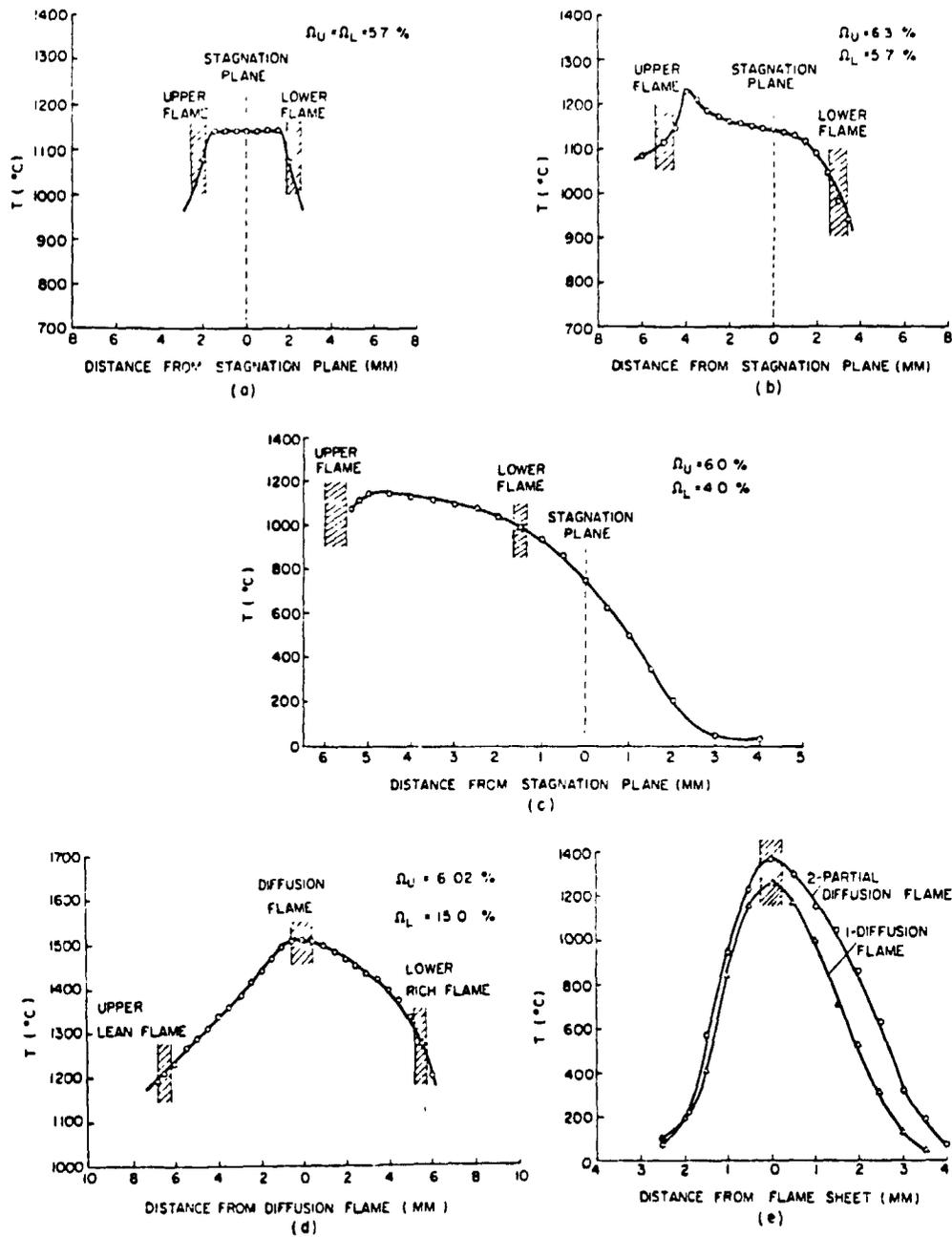


Figure 4. Temperature profiles of methane/air flames: (a) Symmetric flames; (b) Asymmetric flames; (c) Negative flame; (d) Triple flames; (e) 1. Diffusion flame; 2. Partial diffusion flame, concentrations are fuel + 10% stoich.  $\text{O}_2$  in upper flow and air + 10% stoich. fuel in lower flow.

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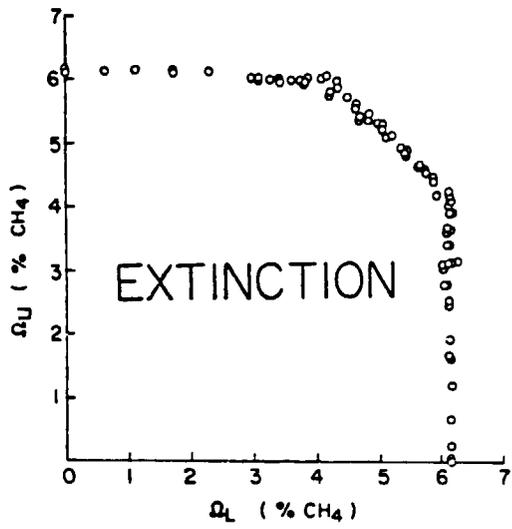


Figure 5. The extinction boundary for two lean premixed methane/air flames.

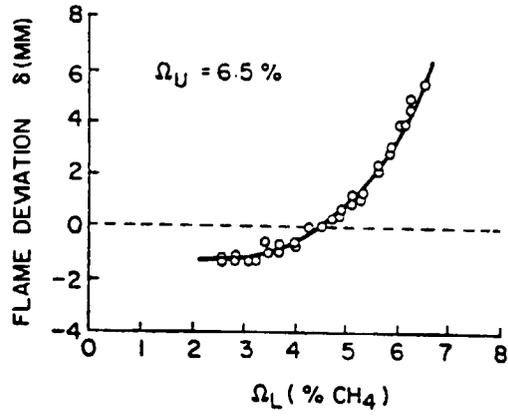


Figure 6. Distance between lower flame and stagnation surface,  $\delta$ , as a function of  $\Omega_L$ .